Case Study of Reinforced Earth Wall Failure during Extreme Rainfall

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ABSTRACT: Recently number of reinforced earth walls had problems such as cracking on the facing wall, breakage of connection pins in the modular block, differential settlement on the foundation and collapsing facing wall. This paper describes the recent application and design for both panel type and modular block type faced reinforced walls. The failure case histories of reinforced earth wall during the extreme rainfall are also presented.

1 INTRODUCTON

The reinforced earth technology was introduced in the construction of earth embankment, castles, and traditional houses with utilizing chopped rice straw or tree branch mixed with mud in the wooden wall frame(Lee, 1998; Kim, 2003).
The modern reinforced earth technology in Korea was first introduced in the year 1980 for the construction of No.3 Highway in Gyeonggi Province. The reinforcing material used in this project is a flat type galvanized steel strip. The reinforced earth technology has been getting widely accepted since then and reached approximately 559 thousand m^2 construction work in the year April 2010 by the government agency and private industry.
Many different types of reinforcing materials like other countries are being used for the reinforced wall. The reinforcing materials for the reinforced wall are mainly stiff geogrid(PP) and flexible geogrid (PET), geosynthetic strip type, galvanized steel strip, and soil nailing. The wire mesh type reinforced steel bar and steel bar with a cross-reinforcing angle are also used for the reinforced wall.

The first part of this paper describes the design criteria of reinforced earth walls incorporation with the quality control of reinforced wall components, that is, facing block, reinforcement material, backfilling soils. The comparison of design criteria of reinforced earth wall between the design methods used in USA(NCMA, FHWA) and the design methods used in several Korean Agencies has been made in the categories of external stability, internal stability, local stability, and design of reinforcement in its length and spacing.
The second part of this paper is introduced the construction procedure of panel type and modular block faced reinforced earth walls. Finally several case histories of reinforced earth wall failure during extreme rainfall are presented with the typical types of the failures, the total collapsing of the wall, facing block collapse, differential settlement of foundation soil, facing wall cracking, and large distortion of facing wall.
Lee and Cho(2010) presented the design and construction data of reinforced earth walls for each regional district where is tabulated in Table 1.

Table1. Construction data of reinforced walls in Korea (Lee and Cho, 2010)

Regional district	No. of construction site	Reinforced wall		
		Design (m^2)	Construction cost (million US＄)	Actual construction(m^2)
Seoul	43	41,279	8.8	99,817
Daejeon	55	375,141	10.0	183,246
Wonju	23	121,726	3.3	33,638
Iksan	61	318,818	8.8	113,603
Busan	67	309,539	8.5	128,519
Total	249	1,544,504	39.4	558,823

2 DESIGN CRITERIA OF REINFORCED EARTH WALLS

The design and construction criteria of reinforced earth wall are fundamental guideline and important parameters in terms of stability and integrity of reinforced earth wall. The quality control guidelines of reinforced earth wall components such as facing blocks (panel type and modular block type), reinforcement material (geosynthetics and galvanized metal strip), and backfilling soil are provided by the Korea Highway Corporation(2009), Korea Slope Construction Design Code(2006), and Korea Structure Foundation Design Code(2009). The detail limit and values for each component are described in Tables 2 and 3.
Most of reinforced earth walls in urban area are being constructed in the hilly area to obtain the marginal land for the parking space or play ground for children in the large scale apartment construction site. In this kind of construction site, it is rather difficult to have a good backfill soil in the reinforced earth wall. Because the Korean Peninsula is mountainous and 70% of the land is covered with mountains.
So, the decomposed weathered granite soil is the major sources of backfill soil around the construction site. The most of construction site use this kind of soil with the removal of large size of boulder.

Table 2. Design criteria of backfill soil for reinforced earth wall in Korea(Lee and Cho, 2010)

Grain size	% of passing
Galvanized metal strip (102mm)	100
Geosynthetics reinforement (19mm)	100
0.425mm(No. 40) 0.075mm(No. 200)	0~60 0~15
PI $\leq$ 6	

Table 3. Quality control of reinforced wall components

Wall component		Korea Highway Corp.(2009)		Korea Slope Construction Design(2006)	Korea Structural Foundation Design(2009)
		Panel type	Block type		
Facing block	Unconfined compressive strength (MPa)	21			Panel: 30MPa block (-)
	Absorption(%)	Average less than 7, Maximum less than 10			
	Manufacturing Deviation (mm)	±3	±5	-	-
Reinforcement material	Geosynthetics	-			
	Galvanized metal strip	610g/m^2		-	5.88N/m^2
Backfilling soil	Internal friction angle	KSF 2343 Direct shear result, greater than design value			Greater than 25°
	Maximum size(mm)	100		53	100
	% of passing NO.200 sieve (75mm)	15		35	15
	PI	6 $\geq$	6 $\geq$	-	6 $\geq$
	PH	5~10	5~10	-	-
	Degree of Compaction (%)	95%(D, E Types compaction)			-
	Lift thickness of compaction (cm)	20		20	-

With consideration of the availability of soil, Tables 2 and 3 give the quality control limit for the backfill soil in the reinforced earth wall.

Table 4. Comparison of design criteria of reinforced earth wall, (earthquake situation) (Lee and Cho, 2010)

<table>
<tr><th colspan="3">Design criteria</th><th>NCMA (1998)</th><th>FHWA (2001)</th><th>Korea Railway (2001)</th><th>Korea Road Design(□) (2000)</th><th>Korea Structural Foundation Design</th><th>Korea Slope Construction Design (2006)</th></tr>
<tr><td rowspan="11">Factor of Safety (F.S)</td><td rowspan="5">External stability</td><td rowspan="2">Basal sliding</td><td rowspan="2">1.5(1.1)</td><td>1.5(75%)</td><td>1.5(75%)</td><td rowspan="2">1.5(1.2)</td><td rowspan="2">1.5(-)</td><td rowspan="2">1.5(1.1)</td></tr>
<tr><td colspan="2">Earth quake: F.S(st) 0.75%</td></tr>
<tr><td>Over-turning</td><td>2.0(1.1)</td><td>L/6 in Soil (75%) L/4 in Rock (75%)</td><td>2.0(75%)</td><td>F.S≤2.0 (F.S≤1.5) e≤L/6(e≤L/4) (soil) e≤L/6(e≤L/4) (rock)</td><td>1.5(-)</td><td>1.5(1.1)</td></tr>
<tr><td>Bearing capacity</td><td>2.0(1.5)</td><td>2.5(75%)</td><td>2.5(75%)</td><td>2.5(2.0)</td><td>2.5(-)</td><td>2.5(2.0)</td></tr>
<tr><td>Overall sliding</td><td></td><td></td><td>1.3(1.0)</td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Internal stability</td><td>Metal strip</td><td rowspan="3">1.0(1.0)</td><td>1.0(75%)</td><td rowspan="3">1.0(-)</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Geogrid</td><td>1.5(75%)</td></tr>
<tr><td>Geosynthetic re-inforcement</td><td>1.5(75%)</td></tr>
<tr><td>Pullout re-sistance</td><td>1.5(1.1)</td><td>1.5(75%)</td><td>2.0(75%)</td><td>2.0(-)</td><td>1.5(-)</td><td>2.0(-)</td></tr>
<tr><td rowspan="2">Local stability</td><td>Connection with facing block</td><td>1.5(1.1)</td><td>1.5(75%)</td><td>-(-)</td><td>1.5(-)</td><td>-</td><td>-</td></tr>
<tr><td>Block shearing re-sistance</td><td>1.5(1.1)</td><td>-(-)</td><td>-(-)</td><td>1.5(-)</td><td>-</td><td>-</td></tr>
<tr><td rowspan="4">Rein-force-ment</td><td colspan="2">L/H</td><td>0.6H</td><td>0.7H</td><td></td><td>0.5~0.7H(with slope and heavy concen-trated load: 0.7H)</td><td>-</td><td>0.7H</td></tr>
<tr><td colspan="2">Minimum length</td><td>0.3m</td><td>2.5m</td><td></td><td>2.5m</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Effective resistance Length(Le)</td><td>0.3m</td><td>1.0m</td><td></td><td>-</td><td>-</td><td>1.0m</td></tr>
<tr><td colspan="2">Max. vertical spacing</td><td>Less than 2X height</td><td>Less than 2X height</td><td></td><td>0.8~1.0m Less than 2X block height</td><td>1.0m</td><td>1.0m</td></tr>
</table>

The typical design methods are proposed by the USA, FHWA (Fedral Highway Administration, 1996, 2001), NCMA method(National Concrete Masonry Association), France MOT method(1980)

England method(British Standard, 1995), and Japan Civil Engineering Research Center method(2000).
The most of these methods are based on the concept of the limit equilibrium analysis. The first two methods are compared with the three Korean design methods in Table 4. The design method of stability analysis for reinforced earth wall is categorized into three parts (1) external stability; basal sliding, overturning, bearing capacity, and overall sliding, (2) internal stability; tensile strength of reinforcement element in breakage, pull-out resistance of reinforcement element, (3) facing wall stability; connector between facing wall and reinforcement, block shearing resistance.
The design parameters of reinforcement element are compared in term of reinforcement length, effective resistance length(Le), and the maximum vertical spacing of reinforcement. The most of Korea design methods are based on the FHWA metohd.

3 PANEL TYPE REINFORCED EARTH WALL

The advanced reinforced earth wall technology in Korea has been used in the past thirty one years. The most of reinforced walls were applied along the highway construction for retaining natural soil slopes, embankment, and approach embankment of bridge flyovers.
The wall facing of reinforced earth wall are generally categorized into two types, either hard concrete facing or geosynthetic soft facing. The most of reinforced earth wall are currently utilizing hard concrete discrete panels, either flat panel type like using in Reinforced Earth Wall(REW) or modular block type. These are usually made of precast concrete with overlapping joints with compressive filler and are made of various sizes and shapes to fit the design requirement.
A flexible soft facing is formed by wrapping each layer of reinforcement around individual compacted soil. The reinforcement is anchored back into the backfill soil by pinning or partially buried. This type of wall facing is usually applied in the temporary retaining wall structures.
Figure 3.1 shows the construction of the reinforced earth wall to gain the extra land for the apartment complex in Youngin, Kyeonggi Province on November, 1996. This marginal land can be used for the parking space and play ground for resident. Many of these kinds of construction techniques are practiced in Korea due to the dwindling of available land in the urban area.
The reinforcing material in this particular project is a belt type continuous strip which made of polyester(PET) with polyethylene(PE) coating. The construction sequences are shown in Figure 3.2. The reinforcement belt strip is stretched and anchored on the facing panel by using a loop attachment and carbon rod(L=17.5cm, D=25mm or 32mm). The reinforced earth wall shown in Figure 3.3 is for Sadang Dealim apartment complex in southwest part of Seoul Metropolitan area on July, 1988. The height of this reinforced wall is about 16m and consists of levels with a small beam in-between the 1st staged wall and the 2nd staged wall(E & S Eng., 1997).


Fig 3.1 Reinforced earth wall for apartment complex in Youngin, Gyeonggi Province.


Fig 3.2 Construction of reinforced earth wall with PET belt type reinforcement.


Fig 3.3 Two stages of reinforced wall in Sadangdong, Daelim apartment complex.

The maximum wall height constructed is 18.3m in Namyangju, Kyeonggi Province for the apartment complex on August, 1994. Figure 3.4 shows the construction of an approach embankment for overpass bridge on Kyeongchung Highway in Seongnam, Kyeonggi Province on November, 1992. These reinforced earth techniques are mostly used in the highway cut to secure the earth slope against sliding failure. The galvanized metal strip which manufactured in Korea is being used as a reinforcement(Figure 3.5). However, the quality is a little bit low as comparing with REW's in terms of mobilizing friction angle and coating along the strip.

Fig 3.4 Reinforced approach embankment for overpass bridge, Kyeongchung Highway**.**

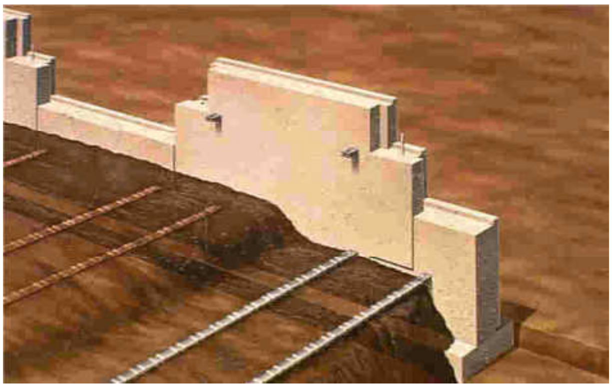


Fig 3.5 Reinforced earth wall construction with galvanized metal strip.

4 MODULAR BLOCK FACED GEOSYNTHETIC REINFORCED WALLS

The modular block faced geosynthetic reinforced segmental retaining walls are extensively used in Korea. The trend of using this type of reinforced wall is very optimistic and very comparative in comparison with the conventional concrete retaining walls. It can be applied in the side wing of an approach embankment of bridge flyovers as shown in Figure 4.1

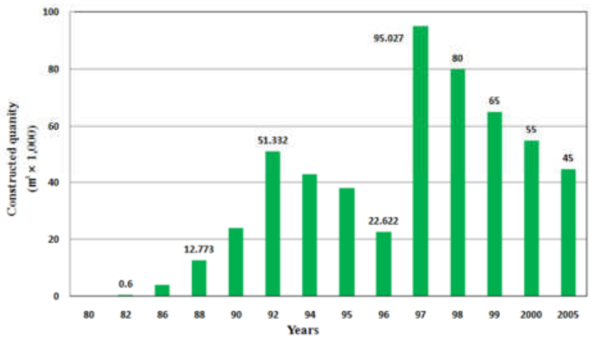
The applications of modular block faced geosynthetic reinforced wall can be categorized into the construction area for the residential & office buildings, construction of apartment complex and industrial factory complex in the hilly area to obtain the building site with cutting off the hillside as shown in Figure 4.2.


Fig 4.1 Modular block faced reinforced wall in an approach embankment of bridge flyover.

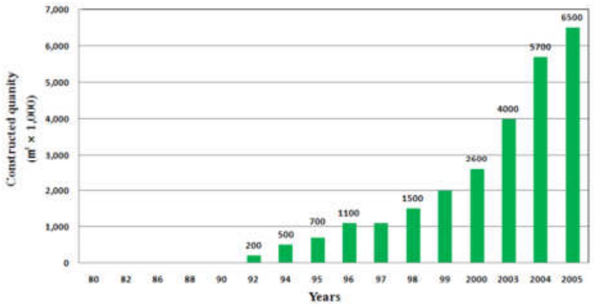

Fig 4.2 Modular block faced geogrid reinforced wall which developed in Korea.

The total amount of construction of both panel type facing reinforced walls and block type facing reinforced walls are presented in Figure 4.3.

The reinforcing materials for modular block faced reinforced walls are mostly polyester geogrid and polypropylene geogrid. Two types of geogrid are used in practice, uniaxial geogrid and biaxial geogrid, depending on the application purpose. Fasteners and connections are necessary in reinforced modular block wall where geogrids are connected to the facing block.



(a) Concrete panel faced reinforced wall.



(b) Modular block type faced reinforced wall

Fig 4.3 Construction amount of geosynthetic reinforced earth walls in Korea.

5 CASE HISTORY OF REINFORCED EARTH WALL FAILURE

The typical failure mode of reinforce earth walls can be classified as facing wall cracking, total wall collapse, facing block collapse, excessive differential settlement, and distortion of facing wall.

The external and internal stabilities failure of reinforced earth walls are schematically drawn in Figure 5.1.

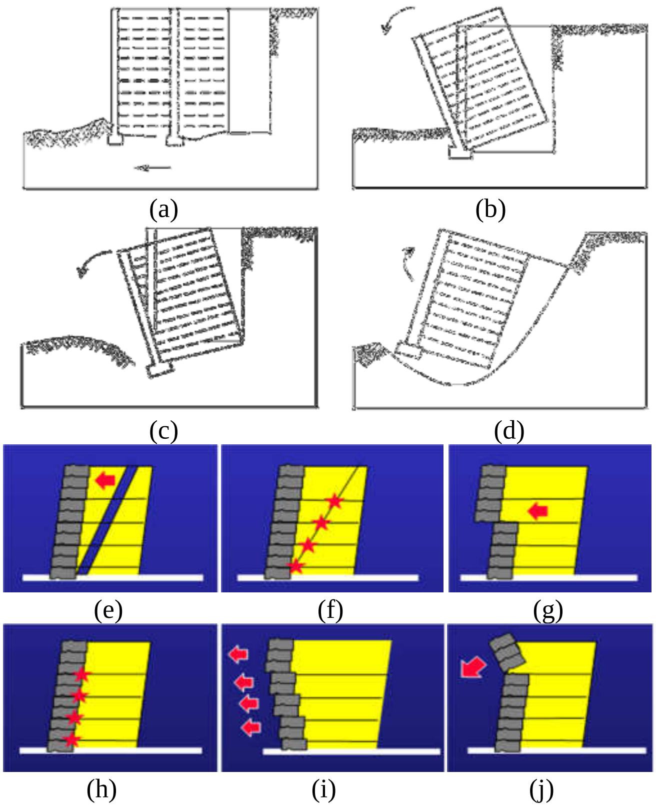


Figure 5.1 Failure modes of reinforced earth wall(External failure (a)basal sliding, (b)overturning, (c)bearing capacity failure, (d)overall sliding; Internal failure (e)Pull-out failure, (f)breakage of reinforcement, (g)internal sliding, (h)breakage of connector, (i)shear failure of facing wall, (j)failure of upper facing block)

The most of troubled reinforced earth walls are being constructed in the hilly area of the mountain valley. Because the large amount of water flow is expected during the extreme rainfall in the rainy season. The level of foundation soil is not uniformed both in the horizontal direction and the longitudinal direction. In the month of August 2010 in Korea, the extremely heavy monsoon rainfall was occurred. The precipitation in a single day was about 671.5mm. Therefore, the proper design of drainage system and the appropriate treatment of foundation soil are the important element to maintain the stability of the reinforced earth wall.

Facing wall cracking can be occurred due to non sufficient unconfined compressive strength of facing wall and non proper connection between facing wall and reinforcement element, excessive tensile strength induced in the curved part of REW, and differential settlement of foundation soil. Figure 5.2 show the case of wall failure by cracking. The pore water pressure was built up at the right bottom corner of the first staged reinforced wall. This problem was also caused by the improper treatment of foundation soil. The place where the pore water pressure builds up was not treated foundation soil with concrete cement like other front part of the wall. Thus, the differential settlement was occurred at the corner of the wall and the earth pressure was concentrated in that area. The ground water was seeping into the corner of the way to create a stability problem of the wall. The remediation for this problem was implemented with monitoring the field instruments such as inclinometer and tilt meters. There were two types of remedial treatments, base reinforcement and drainage control. The cement mortar grouting at the base of reinforced wall around the corner and side part of the wall was injected completely.

Figure 5.2 Facing wall crack of reinforced earth wall

Total collapse of reinforce earth wall could be caused by the lack of stability of overall sliding in design, not sufficient drainage system and bearing capacity of foundation soil, and usage of a lot of fine grained soil as a backfill material and poor soil compaction as shown by Figure 5.3

(a) (b)

Figure 5.3 Total failure of entire reinforced earth wall ((a) Highway construction site - Overall sliding failure; (b) High school construction site - Overall sliding failure and facing block sliding)(Lee and Cho, 2011)

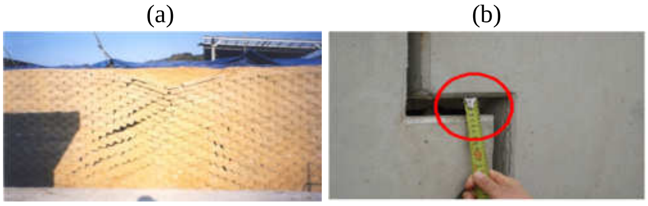
The facing block collapse can be occurred due to the poor design of drainage layer in the behind of reinforce earth wall and broken connector by freezing during winter season. Figure 5.4 shows the failure of facing wall in local road construction site.

(a) (b)

Figure 5.4 Facing wall failure case history (Local road construction area : (a) Deformed of middle part of REW and collapse of facing wall, (b) Facing block sliding)(Lee and Cho, 2011)

The excessive differential settlement of reinforce earth wall foundation soil and the other failure is caused by lacking of compaction for foundation soil for REW where soil banking was implemented, and not sufficient bearing capacity due to improper treatment of foundation soil as shown by Figures 5.5 and 5.6.

(a) (b)



(c) (d)

(e) (f)

Figure 5.5 Excessive settlement and deformation of REW((a) cracking of facing wall, (b) differential settlement of facing wall, (c) settlement of REW, (d) excessive settlement of facing wall, (e) differential settlement of REW, (f)deformation of wall)(Lee & Cho, 2011)

(a) (b)

(c) (d)

Figure 5.6 Failure case history of other reinforced earth wall((a) loss of bottom front banking soil of REW due to poor drainage system in the backfilling area, (b) loss of backfilled soil due to improper construction of backfill area and lack of drainage system, (c) collapse boundary area between cutting area and banking area due to not sufficient drainage system and lack of soil compaction, (d) pull-out failure of reinforcement due to improper soil compaction and lack of pull-out capacity)(Lee et. al., 2011)

6 CONCLUDING REMARK

This paper describes the application of reinforced earth wall, design criteria, and construction problems. The technological level of design and quantity control for reinforced earth wall in Korea is not sufficiently supported to cope with the growth quantity of reinforced earth wall construction market and the increasing number of construction companies. If this problem is being continued, the overall reinforce earth market would be seriously damaged. Based on the statement made above and throughout this study, the following suggestions are made.

(1) The unified standard design and construction criteria of reinforced earth wall should be established with the detail consideration of overall performance and stability.

(2) The development and providing of design soft ware(program) needs to have a reliable design which takes into account the domestic situation of reinforced earth technology in Korea.

(3) The establishment of design review system through the prominent institution to evaluate the design software, design manual, and construction methodology of reinforced earth wall.

(4) The quality control of design and construction, and cost of construction must be seriously executed to construct a high quality of reinforced earth wall.

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